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EFFECT OF SUBSIDENCE ON STRUCTURES BUILT OVER OLD MINING WORKS IN FRENCH IRON BASIN.

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ABSTRACT :

All mining works can generate strata movements and lead sometimes to serious consequences to structures. This paper presents an original analysis of mining subsidence effects on surface structures. We present in the first part of this paper the results of a numerical model, which allows a global understanding of the structure cracking process. A real subsidence profile was applied at the bottom boundary of a finite element model and soil-structure interaction was studied by introducing a simplified structure at the top of the numerical model. A critical analysis was then carried out with the previous parameters which were supposed to be responsible for rupture. The second part is about the built of a better numerical model. This goal led us to make a synthesis of different countries formulas used to estimate the subsidence parameters such as horizontal strains.

RESUME :

Toute exploitation minière peut engendrer des mouvements du terrain et entraîner des conséquences parfois graves sur les structures. Cet article présente une étude originale des conséquences d'affaissements miniers sur des structures de surface. Nous présentons dans un premier temps les résultats d'une étude numérique qui a permis une compréhension globale du processus de dégradation. Un profil d'affaissement réel a été appliqué à la base du modèle et l'interaction sol-structure a été étudiée en introduisant une structure simplifiée à la surface du modèle. Nous procédés à une interprétation critique des paramètres qui sont supposés être à l'origine des dégradations. La seconde partie traite de l'élaboration d'un modèle numérique amélioré. Cet objectif nous a conduit à réaliser une synthèse de formules provenant de différents pays, permettant l'estimation des paramètres d'affaissements comme les déformations horizontales.

1 INTRODUCTION

Many cases of mining subsidence exist around the world. In Lorraine (France), some old iron mines subsided some years ago (Auboué (1996), Moutiers (1997) Roncourt (1999)) so that a lot of houses cracked. Consequences on the population were as much economical than psychological. These mines were exploited by the traditional rooms and pillars method. Subsidence occurs because of the failure of old pillars in areas in which pillars were not removed. There were more than a hundred meters deep and the recovery ratio was ranged between 0,36 and 0,55 in the three latest subsidences. Unfortunately many other villages stand upon old underground works so that the question of consequences of mining subsidence on structure and prediction of damages is asked. An empirical approach is usually used to predict damages according to horizontal strain and the length of the structure (NCB, 1975)

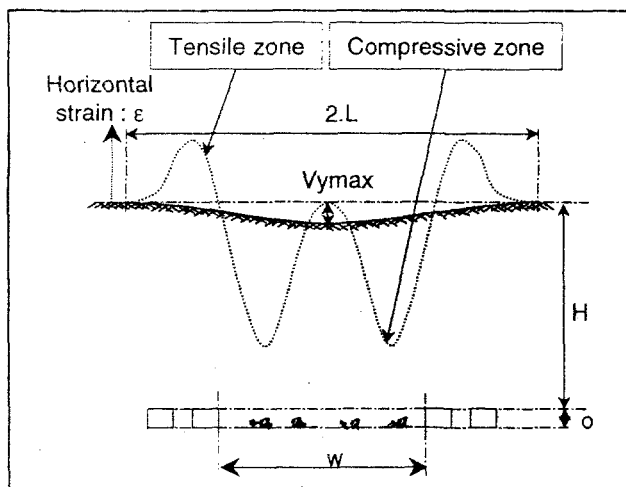


Figure 1 : Horizontal strain profile.

In order to understand the phenomena of degradation, we decided to use a numerical modelling program. It allowed us to observe the soil-structure interaction during the mining

subsidence process. These numerical results reinforced us to improve the model in order to improve the numerical observations efficiency. It is used to consider the horizontal strain on the surface (Figure 1, Aissaoui 1999) to be responsible for damages (Kratzsch 1983). The strain intensity is, hence, very important and seems to be an interesting parameter to compare results of the modelling with field observations. This explains our decision to list formulas of maximum strain estimation from other countries. With these formulas and an analysis about the effectiveness of the numerical model, we propose at the end of this paper a simply realistic model to solicit different kind of structures.

2 NUMERICAL STUDY

2.1 PRESENTATION OF THE MODEL

Our topic is to find a simple model, that allows to observe consequences of soil strains, displacements and curvature on simple surface structure. Because of soil heterogeneities, it is impossible to predict subsidence profile which can occur in a real mining situation with a finite element software. So the purpose of this part is the presentation of an elastic, two dimensional isotropic model which allows to observe the soil structure interaction. The finite elements software "CESAR-LCPC 3.2.4" is used. The model consists of a long soil strip (500 meters long, 50 meters high) with a structure on its top (Figure 2). The structure is modelled by a short homogeneous strip (1 meter high and 25 meters long). Numerical problem is solved with plane strains assumption. So that structure is a 25 m large raft with unlimited proof.

Between soil and structure, we used Goodman's elements in order to model a Mohr-Coulomb interface. Characteristics are the followings : null tensile strength, 30° of friction angle and 0,02 MPa of cohesion.

We impose vertical displacement at the bottom of the soil boundary and observe interaction between the soil and the structure. The bottom boundary displacement is the observed one of a real subsidence that occurred for a 150 meters deep iron mine. Maximum displacement occurred along an hundred meters long on the right of the boundary (1.2 meters) and the minimum displacement along an hundred meters long on the left (0 meter). Thus we can observed no interaction between lateral boundaries conditions and stress-strain values around the structure.

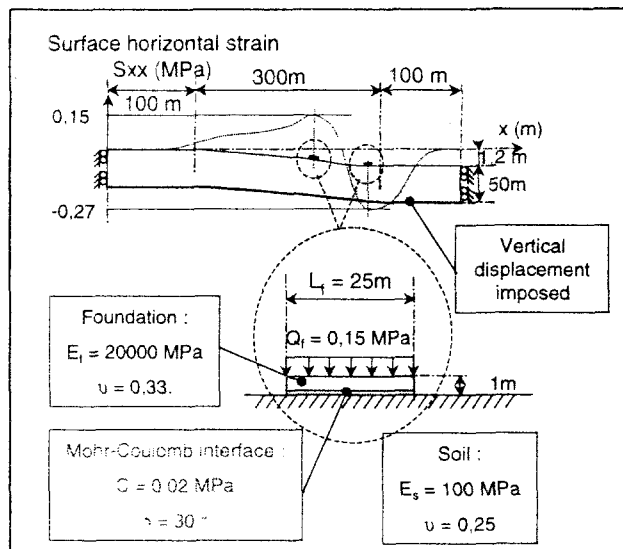


Figure 2 : Numerical model presentation (L_f : foundation length, Q_f : foundation loading, E_f : foundation Young's modulus, E_s : soil Young's modulus).

We realised a parametric study about some foundation characteristics like loading ($Q_f=0.075$ MPa & 0.15 MPa), length ($L_f=10$ m & 25 m) and stiffness ($E_f=10000$ MPa &

20000 MPa). The foundation loading represents a two or four storeyed house. Structure is alternatively placed on the maximum tensile strain area (corresponding to the maximum tensile horizontal stress " S_{xx} ") and in the maximum compressive strain area (Figure 2). The soil structure interaction is viewed by comparison between the stress results of a loaded foundation laying on the soil without subsidence and the model with the vertical displacement applied at the bottom boundary. So our study need 24 computations to be proceeded.

About the model, we agree it to be really simplified and not completely realistic. For example, the soil stiffness is probably not the same along the depth. The foundation can not have the same behaviour as a real building (with foundations, beams, posts, windows) and its regular loading is not realistic because in a house, loading is concentrated under posts. So results must be compared with each other and numerical values do not have to be used alone.

2.2 RESULTS PRESENTATION

We first present results for the case of a twenty five meters long foundation with a Young's modulus $E_f=20000$ MPa, loaded by $Q_f=0.15$ MPa, located in the compression area (Figure 3). The first column presents results for a foundation without subsidence and the second one shows the interaction when subsidence occurs. Curves show parameter variations in the soil along a section under the structure (0.1 meter deep).

About vertical stresses, we observe the consequences of curvature. Compressive area is characterised by a concave geometry which leads to biggest compressive values at the

edges of the raft and smallest at the medium. Horizontal stresses are very different between the initial situation of the raft and after subsidence. We can see no change just under the structure, but a really increase at the edges. This may be explained by the soil-structure interaction. Raft confines soil so that all compressive strains that can not occur under it, occur at the edges. We can see a very important increase of shear stresses, more than 600 %, which is responsible of foundation slipping at the edges. We can argue with such results about the importance of curvature in relation to horizontal stresses. Curvature solicitation seems to be secondary as the vertical stresses variation associated is

very low (less than 15 %) in comparison with horizontal stresses and shear stresses variation (more than 500 %). Such results are corroborated by literature assessments. Neuhaus (1965), Peng and al. (1981), Yokel and al (1982), Bell (1988) wrote that damages would be avoided if shear stresses are decreased. The last conclusion is about parameters values between a subsidence without foundation and with foundation. No doubt that it is impossible to separate soil and structure, and It is wrong to think that subsidence parameters like horizontal strains are completely transmitted to the structure.

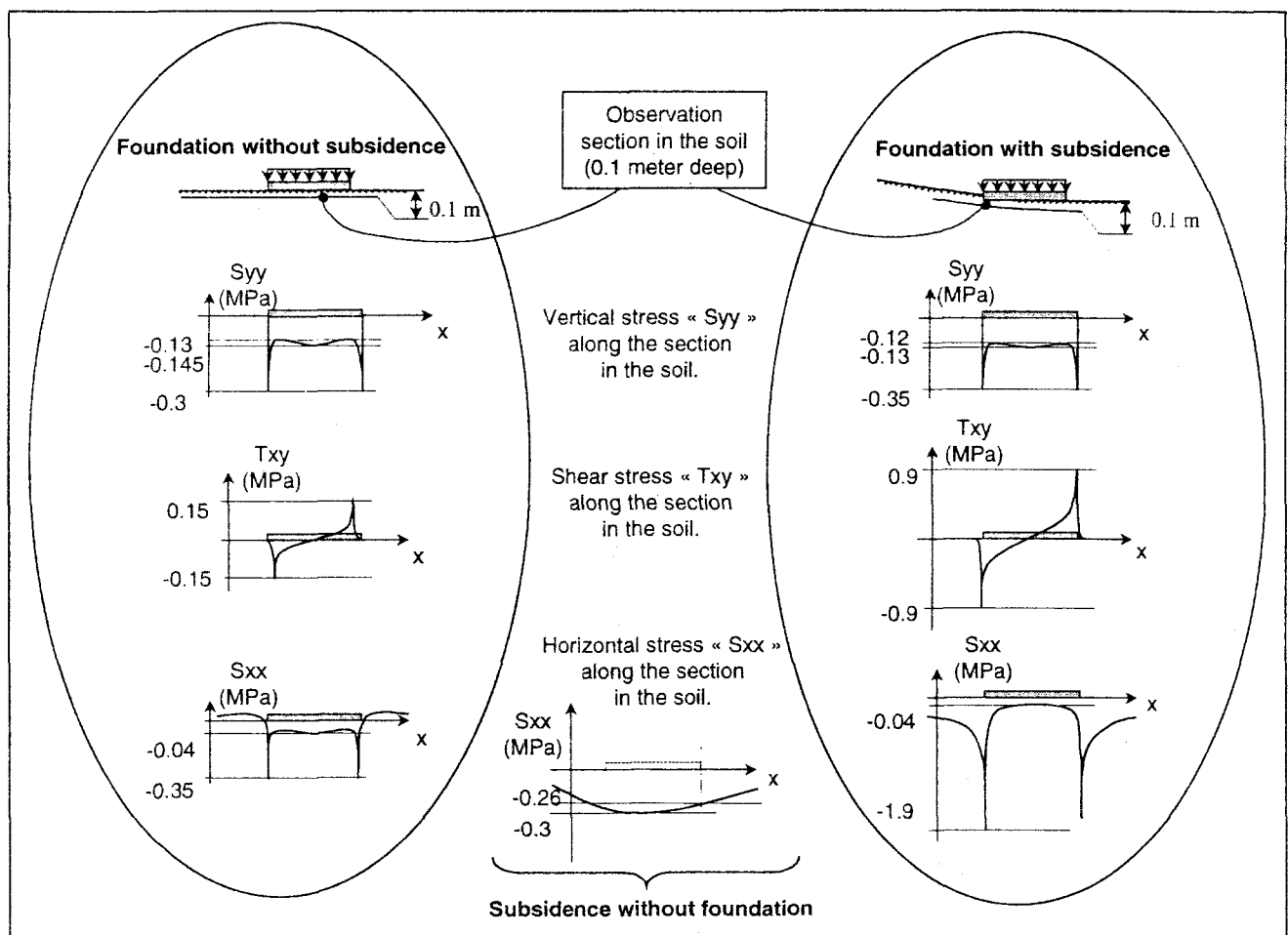


Figure 3 : Stress variation along a 0.1 meter deep section in a compression area ; $E_f = 20000 \text{ MPa}$, $L_f = 25 \text{ m}$, $Q_f = 0,15 \text{ MPa}$.

After this presentation, we can discuss all results for the parametric study. Two statistical analysis have been made to evaluate relative importance of each parameter. The first one consist in a variance analysis, and the second one in an experimental design. We just set out results about relative importance of foundation characteristics to each other which is estimated by computing the stress variation rate when one parameter changes. The stress variation rate is more efficient than absolute change, because it may be compared to the safe coefficients used for the building construction. We remind all the values for the parametric study in table 1.

Table 1 : Parametric values of the foundation characteristics.

Young modulus E_f	10000 MPa ; 20000 MPa
Length L_f	10 m ; 25 m
Load Q_f	0.075 MPa ; 0.15 MPa

Shear stresses in the soil and solicitations in the foundation increase with the length. So length is very harmful. In compressive area, horizontal stresses at the edges of the structure will have very disastrous consequences. The Young's modulus seems not to have influence upon stresses. The reason is probably the big difference between the stiffness of soil and structure. In all cases, structure is dreadfully stiff in relation to the soil. But we notice that stresses in the foundation increase with the structure stiffness. The structure loading appears to be benefit because higher the loading is, smaller the variation rate is. In conclusion, this study allows a better understanding of the phenomena. We have now to improve the geometry of the

structure and to use an elasto-plastic criterion for the soil in order to avoid tensile stresses in the soil which are not realistic. The third improvement is about the bottom boundary condition from which the surface horizontal strains depend. In next section, we present our methodology to obtain a better model at the top of which it will be possible to study different kind of structures subjected to horizontal strains with vertical displacements.

3 HORIZONTAL STRAIN INVENTORY

The maximum horizontal strain evaluation is very important because it is supposed to be one of the more important parameters to explain damages (NCB 1975). So the comparison between numerical values and empirical values is a good way to check numerical strains first estimated. Figure 4 shows values of proportional coefficient "K" to estimate maximum horizontal strain. This coefficient "K" must be multiply by a mining ratio "o/H" or "V_{ymax}/H" in which "o" is the opening of the mining works, "V_{ymax}" is the maximum vertical surface subsidence and "H" the mining depth (Figure 1).

$$[1] \quad \varepsilon_{\max} = K \cdot V_{\max}/H \quad \text{or} \quad \varepsilon_{\max} = K \cdot o/H$$

Each value or range value is refered by a number which allows to know the author. Authors references are the followings : (1) Wagner and Schüman 1985, (2) Kratzsch 1983, (3) Proust 1961, (4) Whittaker and Reddish 1989, (5) Yokel and al.1981. These coefficients result from coal mines

in France, Great Britain, Poland, United States and Germany. We can see a big concentration around the unit value.

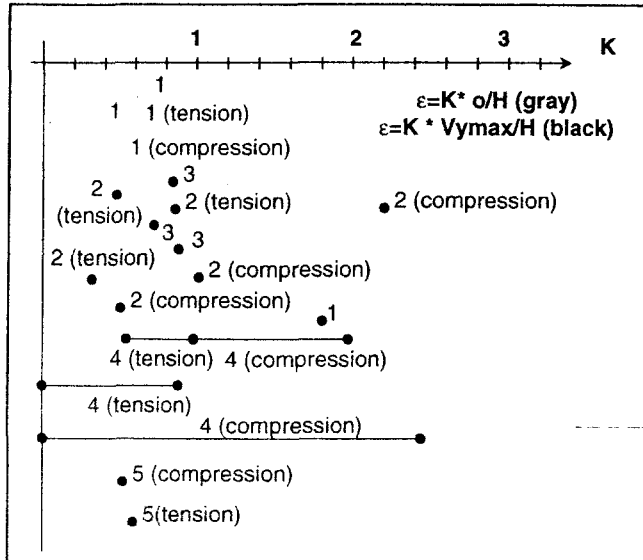


Figure 4 : coefficient of proportionality for the maximum horizontal stress estimation.

If we compare these formulas with results of the first numerical model presented in the second section, we observe a really underestimated horizontal strain. Indeed, the first model was built with a real subsidence profile with a 150 meters deep mining work and a 1.2 m subsidence at the centre. Maximum strain should be about $1.2/150 = 8 \cdot 10^{-3}$ [eq. 1 with $K=1$]. Although we computed a maximum tensile stress of 0.15 MPa and a maximum compression stress of 0.27 MPa. Soil stiffness is of 100 MPa which leads to a maximum horizontal strain of about $1.5 \cdot 10^{-3}$ in tensile area and $2.7 \cdot 10^{-3}$ in compressive area. The difference between both the results may be explained by the small model size which did not contained the mining works. In order to study soil-structure interaction we decided to use an improved numerical model which leads to a good strain rough estimate.

4 NUMERICAL MODEL IMPROVEMENT

We first want to estimate the errors due to the small height and the bottom boundary displacement condition of the previous numerical model. We decided to make a global numerical model which contained the underground mining works. From the results of this global model, a small model which the geometry was exactly the same than in the second chapter is solicited. By comparison of both results, it is possible to estimate the errors made when we try to reproduce real mining effects on the surface in the same way than in chapter two (that is to say with a small model, solicited by a subsidence profile at its bottom boundary).

Global model size is 200 m high and 570 m long. Mining works are 150 m deep, 200 m long and we simulate a 1 meter subsidence. To obtain such a vertical displacement at the centre of the subsidence profile, we impose a unit vertical displacement at the top of the underground excavation (Figure 5). This figure clearly explains our methodology. Vertical displacements computed at the top of the global model are used for the bottom boundary condition of the small model. Results are shown in Figure 6. We can see that we make strong errors when we only use a small model. Vertical displacements are correctly transmitted between the two models, but horizontal strains are divided by about 2.

Maximum horizontal strain grows up to average $3 \cdot 10^{-3}$ when "theoretical" value according to the horizontal strain formulas [eq. 1, with $K=1$], is $1/150 = 6,5 \cdot 10^{-3}$.

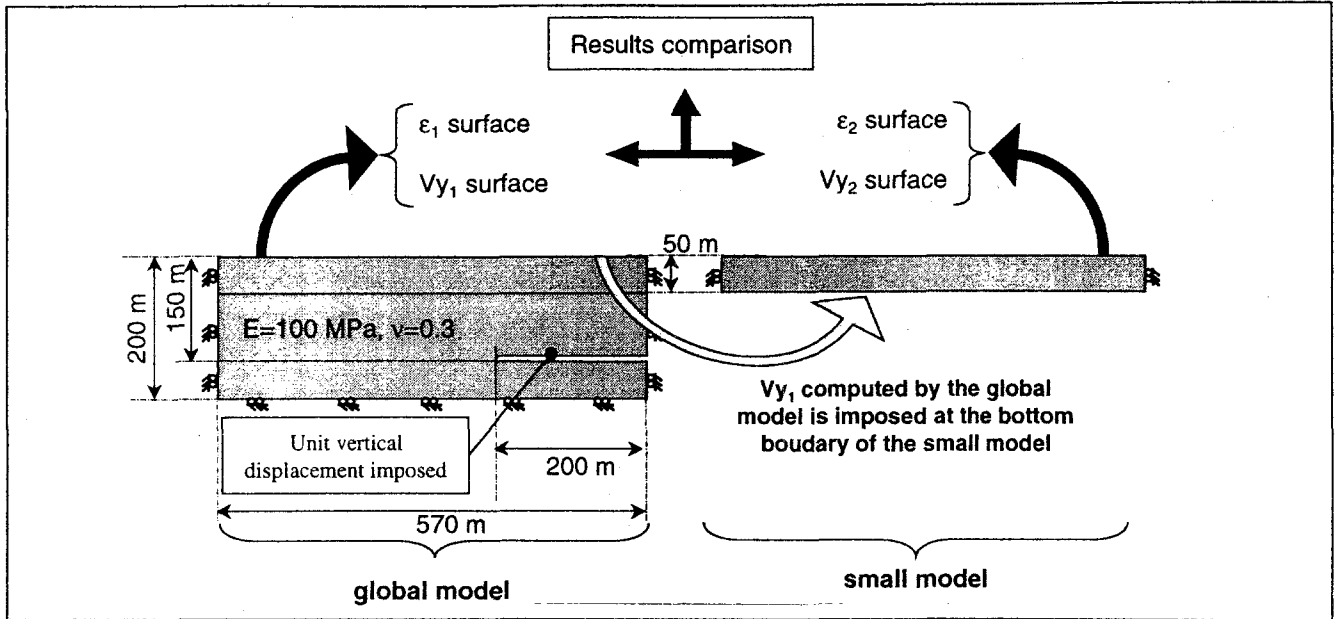


Figure 5 : Comparison between global and small models.

In fact, the two models react like a beam. If we impose a vertical displacement, horizontal strains at the top boundary will increase with the height of the model. Indeed, a fixed vertical displacement leads to a fixed curvature. And we know that for a beam :

$$[2] \sigma = \frac{Mf \cdot h/2}{I}$$

$$[3] Mf = \frac{E \cdot I}{R}$$

$$[4] \sigma = E \cdot \epsilon$$

With " σ " normal stress at the top of the beam, " h " height, " I " moment of inertia, " E " Young's modulus, " $1/R$ " curvature and " Mf " bending moment. Thus :

$$[5] \epsilon = \frac{h}{2 \cdot R}$$

So when the height of the model increases, strains will grow up too.

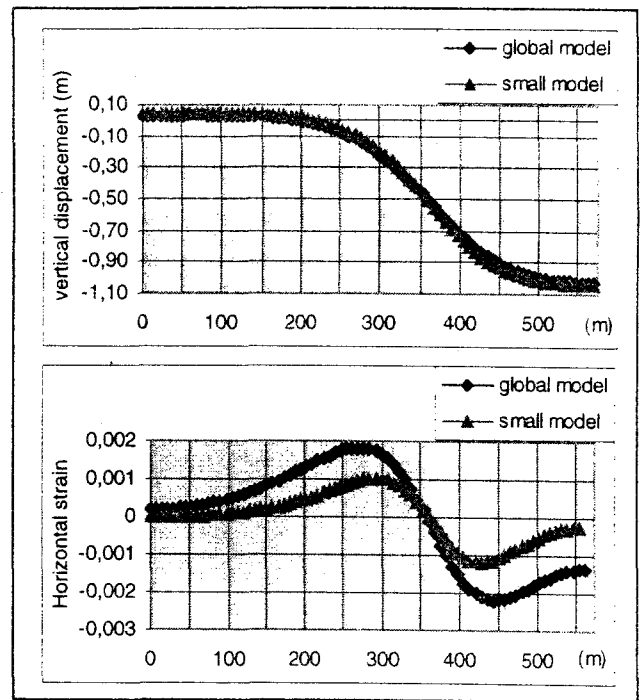


Figure 6 : Vertical displacement and horizontal strain at the surface of the two models.

This leads us to the conclusion in which we offer a new methodology to solicit surface structures. First, we have to know vertical displacements which will be imposed at the

bottom boundary. These should be real subsidence which may occur at the strata. Next, we have to estimate maximum horizontal strain with equation 1 and figure 4. Then it is possible to find the optimal model size length "L" and height "h" with which numerical and real horizontal strains at the surface are the same. We saw that the height increase does not really change the vertical displacement profile, but the higher "h" is and the greater the computed strains will be. "L" must be found in order that the lateral boundaries do not disturb model results.

5 CONCLUSION

Many charts built from visual and practical observations allow to estimate structures damages with only few parameters, but these are not satisfactory. It is why we made numerical models which allow a better understanding of the structure cracking process. A first model allows to estimate the importance of structure length, stiffness and loading to each other. We showed that it was possible to use a simply realistic model to study the soil-structure interaction. In the future we think to improve again and valid this first study in order to use the model with different kinds of post, beam structures and to compare numerical results with those of a statistical study about effects of a real mining subsidence on houses. We hope to be able to improve empirical methods which are usually used to estimate damages.

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